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MULTIACCESS PROTOCOLS FOR VARIABLE LENGTH PACKETS

by

Jacek Jachner

MULTIACCESS PROTOCOLS FOR

VARIABLE LENGTH PACKETS

By

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B.Eng., McGill University
(1981)

Submitted to the Department of
Electrical Engineering and Computer Science
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

at the
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May, 1983

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MULTIACCESS PROTOCOLS FOR

VARIABLE LENGTH PACKETS

By

JACEK JACHNER

Submitted to the Department of
Electrical Engineering and Computer Science
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ABSTRACT

New multiaccess protocols are introduced for a large delay satellite channel carrying bursty, variable length data traffic. A Poisson model is used for the transmission process, and all the stations are assumed to make error-free observations of the channel. High channel utilization is achieved without breaking up variable length messages into fixed length packets; the new protocols offer an alternative to existing Pure and Slotted Aloha protocols.

The Variable Length Slotted Aloha(VLSA) protocol exploits any apriori knowledge about packet lengths to schedule transmissions so as to minimize the risk of collision; the traffic throughput of VLSA is consistently better than that of Pure Aloha for variable length packets. In the Reservation Header Variable Length Slotted Aloha (RHVLSA) protocol, the packet header is used to place a reservation for retransmission if the packet suffers a collision after the header. The traffic throughput for this protocol exceeds 26.9% for any packet length distribution. The message throughput of the RHVLSA protocol is larger than that of Slotted Aloha for certain message length distributions.

Thesis Supervisor: Dr. Robert G. Gallager

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1. INTRODUCTION

Multiaccess protocols govern the sharing of a common resource by a number of independent users; the issue arises for scarce and expensive resources or when a high degree of connectivity between the users is desired. In communication systems, protocols address the problem of controlling access to a common channel so as to efficiently allocate the available communication bandwidth amongst the contending transmitting stations.

The earliest protocols, frequency or time division multiple access, allocated channel bandwidth to the stations in a static fashion, independently of their activity(1). These fixed assignment techniques have proven to be very successful for stream type traffic. Computer traffic however, can often be characterized as bursty, as in the case of interactive terminal traffic. This burstiness is a result of a large degree of randomness in both the message generation times and message sizes, and the relatively small transmission delay tolerated by interactive terminals. A transmitting station that carries traffic from such bursty sources demands the channel rather infrequently, but when it does, it requires a rapid response. In such environments, fixed subchannel allocation schemes would need to assign to each station sufficient capacity to meet its peak transmission rates, which would result in low overall channel utilization. Instead, dynamic allocation of the channel resources is prefered; such is the case in packet communication systems, where the entire channel bandwidth is allocated to a single station, based on need, but only for a short period of time. Transmissions are

formatted into packets, which along with the message data
contain overhead information such as source and destination
addresses, error control bits, and a synchronizing sequence
required for the correct reception of the packet.

The difficulty, then, resides in scheduling these
transmissions on a channel which must carry its own control
information. A class of protocols, called random access(1),
resolves this issue by granting the transmitting stations
full access to the channel according to their randomly
varying needs; since collisions may result, channel perfor-
mance depends on proper collision avoidance and retransmission
scheduling. Another approach is adopted in demand assignment
techniques, or reservation protocols, which require that
explicit control information regarding the stations' need
for the channel be exchanged before message transmissions
are allowed. This avoids packet collisions but the conflict
resolution problem now arises with the reservations themselves.
The channel utilization can be superior to that achievable
with random access, but the reservation placement requirement
imposes a minimum delay on packet transmissions. A number
of adaptive strategies which integrate the two approaches
have been proposed(2),(3), which seek to maintain near-
optimum performance at all times.

The environment in which a multiaccess protocol is
to function is important in its formulation. Protocols
have been designed for satellite channels, ground radio
networks and local area communication. This thesis focuses
on satellite channels, which are characterized by star
connectivity, assuming a satellite can receive signals
from any earth station in its coverage pattern, and can

transmit to all such stations. Another important feature
is the inherently long roundtrip propagation delay of
0.25 sec., which is usually large compared to a packet
transmission time; hence a station is not aware of another
station's transmission while that transmission is in
progress.

The original multiaccess protocol proposed for this
environment was Pure Aloha(4) which was soon modified to
Slotted Aloha(5) and later enhanced by tree conflict
resolution(6),(7),(8). These protocols deal with the
randomness in the message generation times of bursty
sources. The variability in message length is, however,
handled rather poorly; both Slotted Aloha and tree protocols
impose a uniform length for all packets. This seriously
degrades their performance when the message lengths are
non-constant. After a brief overview of these protocols
in the next section, this thesis will introduce a protocol
designed to enhance Pure Aloha performance for packets of
variable length. This Variable Length Slotted Aloha will
be further improved in the last section, where we propose
the use of packet headers to make reservations.

2. RANDOM ACCESS PROTOCOLS

Historically, the first random multiaccess protocol was Pure Aloha, proposed by Abramson(4). It is an inherently simple technique, which permits a station to transmit anytime it desires. Feedback from the channel determines whether a transmission has been successful, or whether a collision has occurred. In the latter case, a retransmission is required, which, to avoid continuing conflicts, is attempted only after a random retransmission delay. If the delays are sufficiently randomized, and the number of stations is sufficiently large, the attempted packet transmissions can be considered to be independent events, with memoryless inter-arrival times. The transmission attempts then form a Poisson process, which leads to a simple analysis of channel performance.

There are several criteria for evaluating multiaccess protocols. High channel bandwidth utilization, or information throughput, is desirable, as is low message delay. For Pure Aloha, the throughput rate of successful packets S, is related to the rate of packet transmission attempts G, which includes both new and retransmitted packets, by the probability of transmission success. For uniform length packets and assuming a Poisson process, the probability that all the stations remain idle for the two packet lengths required for conflict-free transmission is e^{-2G}. Hence,

$$S = G e^{-2G} \qquad\qquad /1/$$

The highest throughput achievable is only 18.4% at $G = \frac{1}{2}$,

due to conflicts and idle time. The throughput decreases
for rates G above the optimal, which makes Pure Aloha
unstable as the channel may enter a clogged state where
many stations attempt transmission but few are actually
successful. The message delay, which is the elapsed time
between message generation and successful reception, can
be characterized by the expected number of transmissions
required for conflict-free reception, which in the steady
state, is just G/S.

The throughput of the Aloha technique may be improved
by slotting the channel time, as first proposed by Roberts(5).
Slotted Aloha requires that any packets wishing to begin
transmitting do so only at slot boundaries, and terminate
their transmission within one slot; thus packet lengths
are restricted to fit within one slot. This technique
prevents mid-packet collisions and doubles the packet per
slot throughput to a maximum of 36.8% with

$$S = G \, e^{-G} \qquad\qquad /2/$$

Slotted Aloha is still unstable, but various stabilizing
control algorithms have been proposed(9).

Subsequent improvements in conflict resolution
have led to the tree algorithms(6)-(8). Information about
collisions is used to reschedule collided packets as if
traversing a tree, decreasing the probability of collision
at each retransmission. Such approaches yield the twin
benefits of throughput values of 43-48%, and of stable
performance at these levels. These techniques, however,
are designed to resolve conflicts only between uniform

length packets, and, as we point out in the next section,
their performance suffers if the message generating sources
serviced by the transmitting stations produce messages of
variable length.

3. VARIABLE LENGTH MESSAGES

The random access protocols discussed so far deal
with the randomness in the message generation times of
bursty sources. The other random aspect of such sources
is the variation in message size. Variable length packets
can be used in a Pure Aloha protocol, but as shown by
Ferguson(10), the system performance deteriorates from
the optimum when packets are of equal length. For Slotted
Aloha and tree conflict resolution algorithms, uniform
packet lengths are a design requirement. For these
protocols, variable length messages generated by the
sources must be formatted into fixed length packets.
This however, reduces the actual message part of the
throughput S for both the short messages, which leave
part of the packet unfilled, and for the long ones which
must be broken up into several packets and incur the
overhead costs for each. Even with the optimal selection
of the packet length for a given message length distribution,
the throughput advantage of these protocols over Pure
Aloha is seriously degraded for variable length messages(10).
The breaking up of long messages also increases the comple-
xity of the system, requiring packet numbering and message
buffering at the receiver.

A multiaccess protocol specifically designed for
variable length messages would avoid these drawbacks;
we shall now propose a protocol which achieves significant
throughput gains over Pure Aloha without restricting
packets to be uniform in length.

4. VARIABLE LENGTH SLOTTED ALOHA

In this section, we introduce an effective protocol
which extends the advantages of channel time slotting to
non-uniform length packets. Any apriori knowledge of the
lengths of packets is used to schedule transmissions so
as to minimize the risk of collision.

The packet structure in our formulation of the
data communication channel constrains the length of the
packet to be at least the length of the overhead infor-
mation in the header. We slot the channel time on the
minimum packet length, with packet transmissions beginning
exclusively at slot boundaries, but allowed to continue
through several slots. Transmission starting times are
further restricted to coincide with what we shall call
starting slots, whose selection may vary for different
packet lengths. Packet transmissions which last i slots
are assigned starting slots every i slots, to create a
Slotted Aloha environment amongst packets of a given
length.

Interference between different length packets is
minimized, for any packet length distribution, if at
least one slot on the channel is chosen as a starting
slot for packets of all lengths. Overlap between packets
is further reduced if the longer packet lengths are
restricted to be integer multiples of all shorter ones,
that is, if the packet lengths are mutually divisible.
In such a case, both the starting and ending slots of a
packet coincide with the corresponding slots for any
shorter packets. The number of starting slots for packets

whose transmission would overlap the transmission of a packet of length i is thus restricted to i/j starting slots for packets of length j, for $0 < j \leq i$, and exactly one for any packets longer than i.

An implementation of such a channel is shown in figure 1, with packets of length 2^k ranging from one slot long header-only packets, which may be used to send very short messages, up to the longest 2^m slot packets. This length distribution yields the largest number of different length packets for any upper limit on packet length, but it is not unique in satisfying the mutually divisible lengths condition.

The assumptions used in the analysis of such a protocol are similar to the ones for Slotted Aloha. The stations are assumed to be time synchronized with the slots on the channel. All the stations listen to the channel traffic and make error-free observations of the outcome of transmissions. There is a delay in making such observations which exceeds the maximum packet length; hence the stations are unaware of the outcome while a transmission is still in progress. Messages are either correctly received or are completely destroyed by a collision and must be retransmitted. If the stations are numerous enough and the retransmission times are sufficiently randomized, the transmission attempts can be considered to be independent with memoryless inter-arrival times, thus forming a Poisson process.

FIGURE 1. VLSA Channel Structure

packet lengths 1 to 2^m slots
(illustrated m = 3)
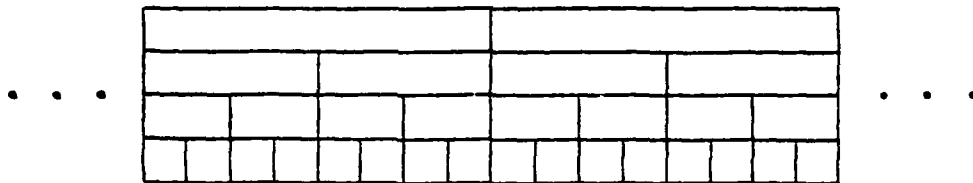
The attempted traffic transmission rate, G, is measured in slots per slot of channel time. Packets of length $l_k = 2^k$ account for a fraction γ_k of this rate, that is for $G_k = \gamma_k G$ slots of traffic per slot of channel time, or G_k packets every 2^k starting slot. The packet transmission rate for packets of length l_k is $1 / l_k$ of the traffic transmission rate for such packets. The traffic throughput S is the rate of successfully transmitted traffic slots per channel slot, of which a fraction γ_k is in 2^k long packets. Such packets successfully carry traffic at a rate of $S_k = \gamma_k S$, which is just the rate of attempted traffic transmissions which do not suffer collision:

$$S_k = G_k \times Pr(\text{channel idle at start}) \qquad /3/$$
$$\times Pr(\text{idle for } 2^k \text{ slots} | \text{idle at start})$$

Due to the Poisson nature of the transmission process, a packet will survive if there is no other transmission during its starting slot, an event of probability e^{-G}, and no other transmissions start until the end of the 2^k long packet. The channel structure limits transmissions after the starting slot to be shorter packets, and these occur at a combined rate of $\beta_k G$, where β_k is defined for packets of length l_k as:

$$\beta_k = \sum_{j=0}^{k-1} \left(\frac{l_k}{l_j} - 1 \right) \gamma_j$$

$$\qquad\qquad\qquad /4/$$

$$\beta_k = \sum_{j=0}^{k-1} \left(2^{k-j} - 1 \right) \gamma_j$$

The probability that no such transmissions occur is then $\exp(-G\beta_k)$. The traffic throughputs for individual packet lengths as well as for the entire channel can be expressed as

$$S_k = G_k \; e^{-G \; (\; 1 \; + \; \beta_k \;)} \tag{/5/}$$

$$S = G \; e^{-G} \sum_{k=0}^{m} \gamma_k \; e^{-G\beta_k} \tag{/6/}$$

The distribution of traffic throughput amongst the packet lengths is related to the attempted transmission rate distribution by the transformation

$$\varphi_k = \frac{S_k}{S} = \frac{\gamma_k \; e^{-G\beta_k}}{\sum\limits_{i=0}^{m} \gamma_i \; e^{-G\beta_i}} \tag{/7/}$$

Since the γ_k's are fractions that sum to unity, the following relation results from equation /7/.

$$1 = \left[\sum_{k=0}^{m} \varphi_k \; e^{G\beta_k} \right] \left[\sum_{i=0}^{m} \gamma_i \; e^{-G\beta_i} \right] \tag{/8/}$$

The reverse transformation to that in equation /7/ is now obtained using /8/.

$$\gamma_k = \frac{G_k}{G} = \frac{\gamma_k \, e^{G\beta_k}}{\displaystyle\sum_{j=0}^{m} \gamma_j \, e^{G\beta_j}} \qquad \text{/9/}$$

The packet length distribution is most usefully specified for newly generated packets, which, in the steady state, is the same as the distribution of successfully transmitted packets. The throughput equation /6/ can be restated, using /8/, in terms of the traffic throughput fractions γ_k:

$$S_k = \gamma_k \, S \qquad \text{/10/}$$

$$S = \frac{G \, e^{-G}}{\displaystyle\sum_{k=0}^{m} \gamma_k \, e^{G\beta_k}} \qquad \text{/11/}$$

Equations /4/ and /9/ can be combined to express β_k in terms of the γ's:

$$\beta_k = \frac{\displaystyle\sum_{j=0}^{k-1} (2^{k-j} - 1) \, \gamma_j \, e^{G\beta_j}}{\displaystyle\sum_{i=0}^{m} \gamma_i \, e^{G\beta_i}} \qquad \text{/12/}$$

We can determine the traffic throughput S, given
any distribution φ_k and attempted traffic transmission
rate G, by numerically solving the implicit equations for
the β_k's. The throughput varies with G as in the Aloha
protocols, increasing to reach a maximum and then decreasing.
The throughput value at the maximum varies with packet
distribution, as shown in figure 2 for the case of two
packet lengths, one twice as long as the other; it is
upperbounded by e^{-1}, which is attained only if all traffic
consists of one packet type. The maximum possible through-
put for any distribution φ decreases as the number of
allowed packet lengths increases, as shown in figure 3
for traffic equally distributed over allowed packet types.

The analysis of the Variable Length Slotted Aloha,
or VLSA, channel can easily be extended to evaluate Pure
Aloha performance for variable length packets. All the
equations /5/ through /11/ still apply, only the form of
the β_k equations /4/ and /12/ is changed. For Pure Aloha,
transmission starting times are not restricted, hence the
rate β_{PAk} G of transmissions which may interfere with a
transmission in progress is larger than that for VLSA.
In fact, for Pure Aloha, with packets of length l_k
comprising a fraction γ_k of the attempted transmission
traffic and φ_k of the successful transmission traffic,
the rate β_{PAk} G is just the sum of the attempted packet
transmission rates, γ_j / l_j, over all packet lengths
and for the duration of transmission l_k.

$$\beta_{PAk} = \sum_{j=0}^{m} \frac{l_k}{l_j} \gamma_j \qquad \text{/13/}$$

FIGURE 2. Maximum Throughput v.s. Small Packet Fraction

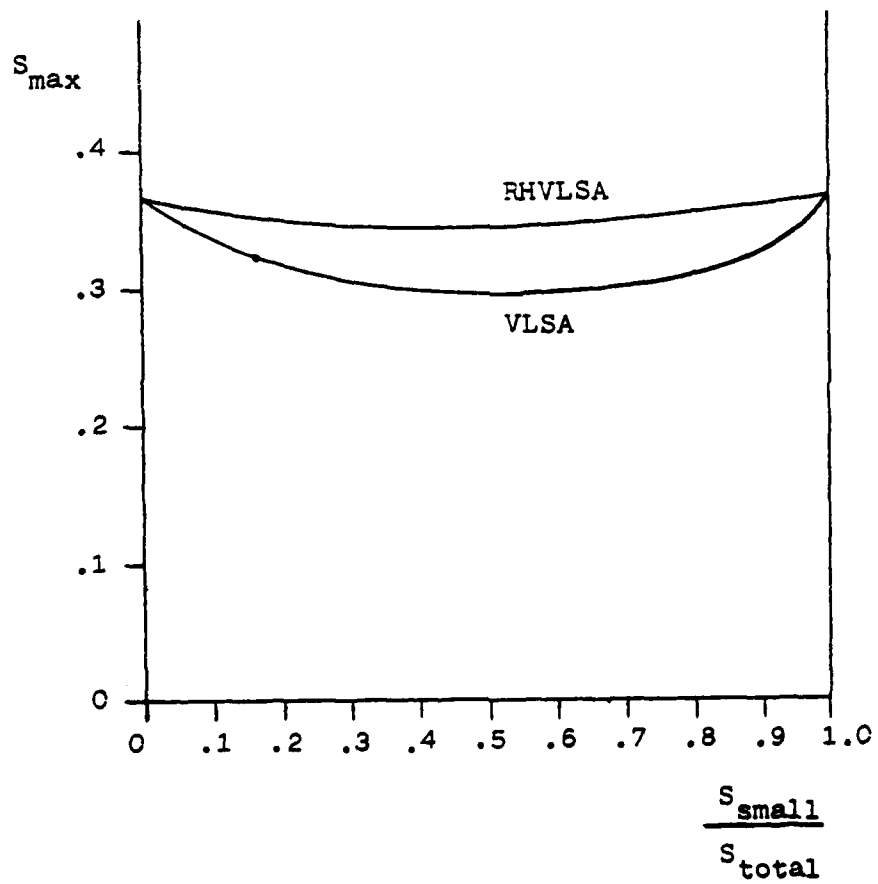　　　　　　　2 packet lengths
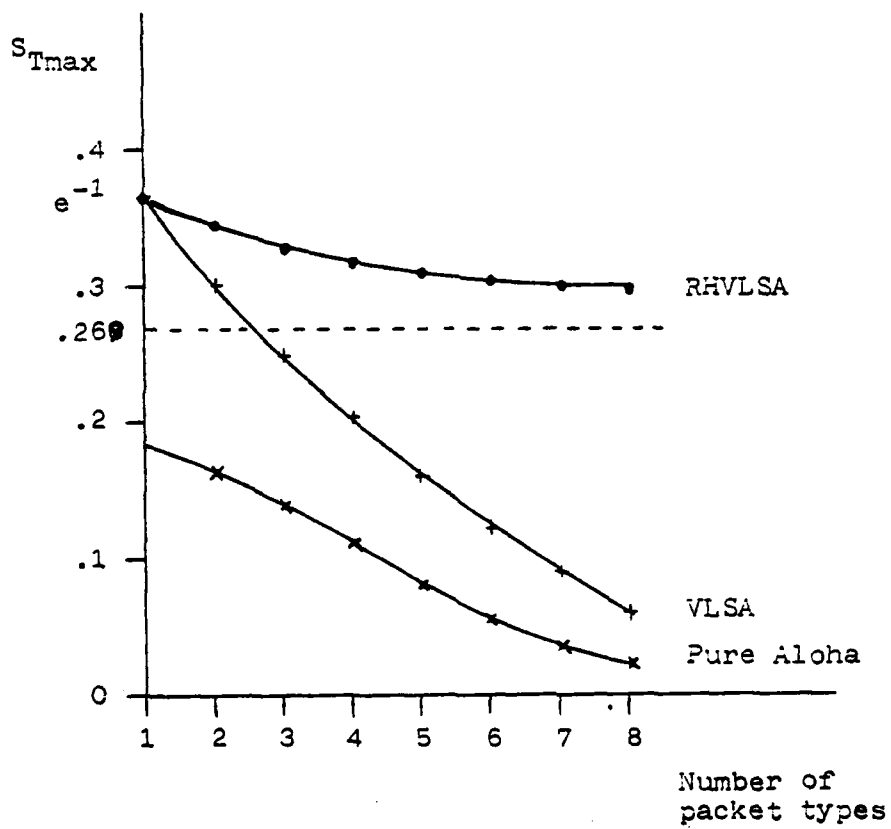　　　　　　　length ratio 2:1

FIGURE 3. Maximum Throughput v.s. Number of Packet Types

packets are 2^k slots long
traffic throughput is equally distributed

$$\beta_{PAk} = \frac{2^k \sum_{j=0}^{m} 2^{-j} \gamma_j e^{G\beta_{PAj}}}{\sum_{i=0}^{m} \gamma_i e^{G\beta_{PAi}}} \qquad /14/$$

A comparison of equations /12/ and /14/ shows that β_{PAk} always exceeds β_k for VLSA, hence the traffic throughput is always larger for VLSA. The throughput performance of the two protocols is compared in figure 3, for traffic equally distributed over variable length packets. VLSA achieves a significant improvement over Pure Aloha for any packet length distribution, but the throughput of both protocols tends to zero as the number of packet types and the ratio of allowed packet lengths becomes large.

It should be noted that in the VLSA protocol, as in Pure Aloha, the attempted traffic transmission rate and traffic throughput rate ditributions differ. In fact, from equation /9/,

$$\frac{\gamma_k}{\gamma_k} = \frac{e^{G\beta_k}}{\sum_{j=0}^{m} \gamma_j e^{G\beta_j}} \qquad /15/$$

This ratio increases monotonically with k, since β_k, as defined in /12/, is also a monotonically increasing function of k. Hence, the protocol is not fair in the sense that the transmission delay varies for different length packets; the expected number of transmissions

required for a 2^k long packet is:

$$\frac{G_k}{S_k} = \frac{\gamma_k \, G}{\mu_k \, S} \qquad\qquad /16/$$

The long packets are more likely to collide on the channel, hence incur longer delays since they require more retransmissions than short packets.

This fairness problem can be remedied by a modification to VLSA which we shall introduce in the following section; in addition, the channel throughput will thereby be improved.

5. RESERVATION HEADERS

Appropriate scheduling of packet transmissions in
the VLSA protocol described above restricts the collision
time from exceeding the length of the longest of the collided
packets. Packets are assumed to be completely destroyed
by a collision, even though the variable length packets
may not overlap on their entire lengths. We will now show
that relaxing this assumption allows useful information
to be obtained from collisions, which, if used to resolve
the conflicts, leads to significant improvements in the
protocol's performance.

In a collision between packets of different lengths,
parts of the longer packet are not interfered with by the
shorter one, and could be useful if they were correctly
received. Correct reception occurs only if the receivers
can lock-in on the transmission by recognizing the synchro-
nizing sequence in the packet header. Should this sequence
be corrupted by a collision, no further part of the packet
can be decoded. For a collision which occurs anytime after
the header, the receiver decodes the packet but the error
check bits at the end show the reception is incorrect.
The extent of the damage cannot be determined unless there
are additional error checks on the packet parts. In
particular, the inclusion of an error detecting capability
in the overhead at the beginning of the packet allows the
header to be decoded independently. An attempted trans-
mission now leads to one of three outcomes:
1. Entire packet successful
2. Header successful, message part suffered collision
3. Entire packet is destroyed

The headers, being shorter that entire packets, have a better chance of survival in the contention environment, and can be used to resolve conflicts. A header decoded correctly not followed by a correctly decoded message, can reserve future channel time for the packet retransmission, providing the header contains packet length information. The station which placed the reservation retransmits the entire packet after a fixed delay sufficient for all the other stations to have heard the reservation. The other stations, aware of the request and of the length of the packet, refrain from transmitting during that time.

The channel can be in one of two modes. In the contention mode, stations compete to transmit packets or at least reservation headers, which are then harboured during the conflict-free reserved mode. The VLSA protocol is used while in the contention mode, with the first slot of each packet acting as a reservation header. As illustrated in figure 4, packets which have placed reservations are delayed until the end of the VLSA frame in progress, each frame being as long as the longest allowed packet. At that time all are serviced, in the order of reservation header transmission, including any reservations that arrive while the channel is in the reserved mode; only then does contention resume.

In the analysis of this Reservation Header Variable Length Slotted Aloha, or RHVLSA, channel, we denote the attempted traffic transmission rate during contention as G_C, with a fraction γ_k in 2^k long packets, and the traffic throughput rate in contention as S_C. In addition, we

FIGURE 4. RHVLSA Channel
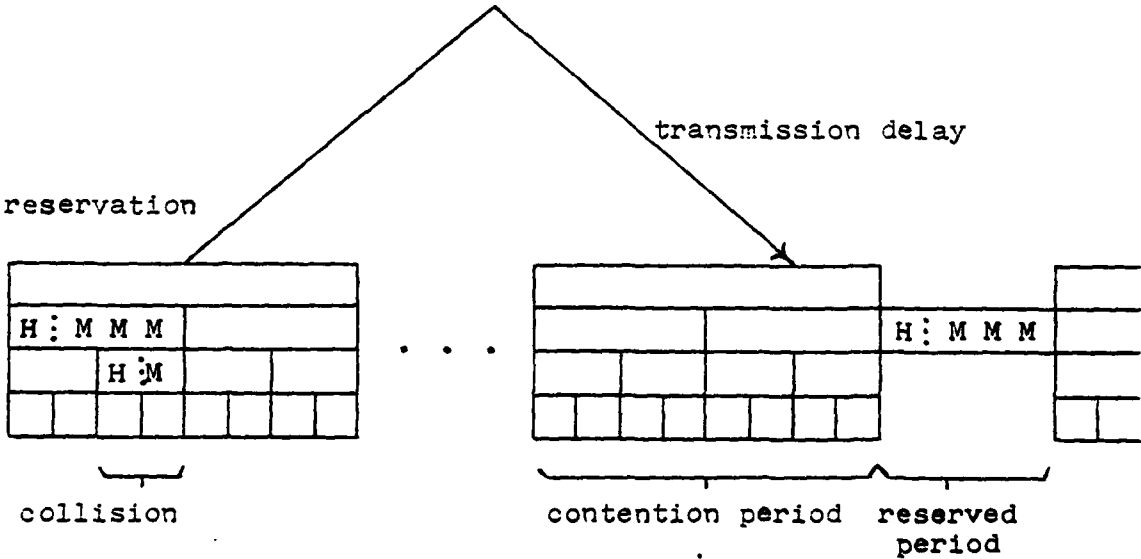
define R_{ck} as the traffic slots per contention slot, which are in packets 2^k long whose headers have not incurred collision. Again using the Poisson nature of the transmission process,

$$R_{ck} = G_{ck} \ e^{-G_c} \qquad\qquad /17/$$

The entire packet will succeed if the header is successful, and no interfering packets transmit while the transmission is in progress. The VLSA channel structure limits the rate of such transmissions to $\beta_k \ G$; hence,

$$S_{ck} = R_{ck} \ e^{-G_c \beta_k} \qquad\qquad /18/$$

where

$$\beta_k = \sum_{j=0}^{k-1} \ (\ 2^{k-j} - 1 \ ) \ \gamma_j \qquad\qquad /19/$$

Packets with successful headers but corrupted messages generate reservations at a rate of G_{rk} (slots of traffic in 2^k long packets per contention slot).

$$G_{rk} = R_{ck} - S_{ck} \qquad\qquad /20/$$

$$G_r = \sum_{k=0}^{m} G_{rk} \qquad\qquad /21/$$

The total throughput S_T, for both channel modes, is easily obtained by observing that any packet whose header succeeds by contention is assured of successful transmission, either immediately, or in the reserved mode. The total throughput is then the rate of successful headers scaled by the fraction of channel time spent in the contention mode.

$$S_{Tk} = \frac{R_{ck}}{1 + G_r} = \frac{G_{ck} \, e^{-G_c}}{1 + G_r} \qquad /22/$$

$$S_T = \sum_{k=0}^{m} S_{Tk} = \frac{G_c \, e^{-G_c}}{1 + G_r} \qquad /23/$$

Using equations /17/, /18/, /20/, /21/, we express G_r as

$$G_r = G_c \, e^{-G_c} - G_c \, e^{-G_c} \sum_{k=0}^{m} \gamma_k \, e^{-G_c \beta_k} \qquad /24/$$

Since the probability of header success is the same for all packets, the traffic throughput distribution is equal to the contention channel attempted traffic transmission distribution; from equations /22/ and /23/ we have:

$$\gamma_k = \frac{G_{ck}}{G} = \frac{S_{Tk}}{S} = \gamma_k \qquad /25/$$

This important feature of RHVLSA makes the protocol fair in the sense that the expected number of transmissions

in the contention mode is the same for all packet classes.

$$\frac{G_{ck}}{S_{Tk}} = \frac{G_c}{S_T} \qquad \forall k \qquad /26/$$

The packets that use the reserved mode do however, incur one additional transmission delay.

To illustrate the protocol, consider a channel with only two packet types, one twice as long as the other, which is slotted on the short packet length. Further let the traffic throughput rate be the same for both packet types $\gamma_0 = \gamma_1 = \frac{1}{2}$; the traffic throughput is plotted in figure 5 with respect to G_c. All short packets are transmitted on the contention channel; in contrast, only some of the long packets succeed by contention, while the rest make reservations. The greater vulnerability of long packets in the contention mode is exactly compensated for by transmissions in the reserved mode.
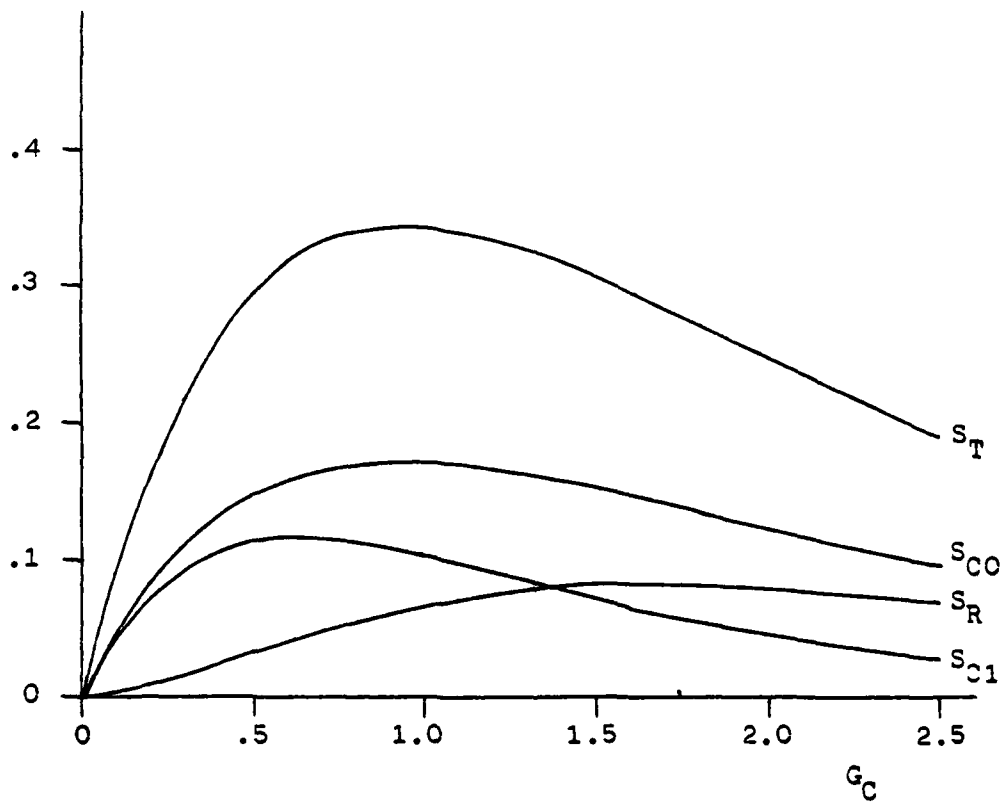
The maximum traffic throughput S_T is achieved for the value of G_c which satisfies the equation $\frac{dS_T}{dG_c} = 0$

which reduces to

$$1 = G_c + G_c^2 e^{-G_c} \sum_{j=0}^{m} \gamma_j \, \beta_j \, e^{-G_c \beta_j} \qquad /27/$$

FIGURE 5. Two Packet RHVLSA Channel

2:1 packet length ratio
equal traffic throughput

This maximum throughput depends on the distribution of traffic amongst the packet types. For the two packet type channel, with a 2:1 packet length ratio, figure 2 shows how S_{Tmax} varies with P_0, decreasing from e^{-1} for a single packet type channel. The reservation header protocol is clearly less sensitive to the packet distribution than VLSA alone.

As the number of allowed packet lengths increases, the maximum throughput decreases as shown in figure 3 for the case of equally distributed throughputs. The RHVLSA protocol is more robust than VLSA, maintaining throughput levels of around 30% even for packets with length ratios of 64:1. In fact, since G_r, as defined in equations /20/ and /24/, is upper bounded by $G_c \exp(-G_c)$ even if no packets succeed in the contention channel, the reservation header protocol throughput S_{Tmax} is always lower bounded by:

$$S_{Tmax} \gg \left. \frac{G_c e^{-G_c}}{1 + G_c e^{-G_c}} \right|_{G_{copt} = 1} \qquad /28/$$

$$S_{Tmax} \gg \frac{1}{e + 1}$$

Thus regardless of the traffic distribution and the number of allowed packet lengths, the RHVLSA traffic throughput will always exceed 26.9%. In fact, since the β's have been eliminated from equation /28/, 26.9% is a lower bound even for a reservation header protocol without the VLSA restriction of mutually divisible packet lengths.

Due to packet overhead, the throughput of actual
messages S_m of any protocol is only a fraction ξ, called
the transmission efficiency, of the traffic throughput.

$$S_m = \xi \, S_T \qquad\qquad /29/$$

For Slotted Aloha, Ferguson(10) defined this efficiency
in terms of the mean message length $\overline{m}$, the mean number
of packets per message $\overline{n}$ and the packet length L_p.

$$\xi_{SA} = E\left[\frac{\text{length of message}}{\text{length of transmission}}\right] = \frac{\overline{m}}{\overline{n} \, L_p} \qquad /30/$$

For variable length protocols, with messages of length l_m
transmitted using n_k packets of length l_k, the transmission
efficiency is

$$\xi_{VL} = E\left[\frac{l_m}{\sum\limits_{k} n_k \, l_k}\right] \qquad\qquad /31/$$

A comparison can now be made between the message
throughputs of Slotted Aloha and variable length protocols.
For message lengths which closely match the allowed packet
lengths, the superior transmission efficiency of RHVLSA
gives it a message throughput advantage over Slotted
Aloha, since less overhead is required when entire messages
are sent in single packets. For instance, consider a two
packet type RHVLSA channel, with a 2:1 packet length ratio
and equally distributed traffic throughput; the short
packets are therefore twice as numerous as the long ones.
Furthermore, we assume that the overhead comprises half
of the short packet length, and a quarter of the long

packet length. This channel would be best utilized if it were servicing a source which produced short messages, equal in length to the overhead, at twice the rate of long messages, which were three times as long as the overhead. The traffic throughput of RHVLSA for this packet length distribution is shown in figure 3 to be 34.4%, and the transmission efficiency, given the message length distribution, can be determined from equation /31/ to be .625 . Slotted Aloha traffic throughput, from equation /2/, is 36.8%, but the transmission efficiency calculated using equation /30/ is at most .5, even for the optimal choice of packet length L_p. The message throughput of RHVLSA and Slotted Aloha are then, using equation /29/, 21.5% and 18.4% respectively; the variable length protocol is better suited for traffic from sources which produce messages with the postulated length distributions.

6. CONCLUSIONS

The multiaccess protocols we have introduced provide
an alternative to the breaking up of variable length
messages into fixed length packets. In the Variable
Length Slotted Aloha protocol, apriori knowledge about
packet lengths is used to schedule transmissions to
minimize the risk of collision. The performance of VLSA
bridges the gap between Pure and Slotted Aloha, with
channel traffic throughput always better than that of
Pure Aloha. The protocol discriminates against long
packets, which incur a longer transmission delay.
Furthermore, traffic throughput is sensitive to the
distribution of packet lengths, and falls to zero as the
number of allowed packet lengths becomes large.

Reservation headers have been proposed as a method
of compensating for the deleterious effects of long packets
in the VLSA protocol, since reservations are most advan-
tageous when the ratio of packet to reservation header
length is large. The reservation header protocol is fair
in the sense that the expected number of transmissions in
the contention channel is the same for packets of any
length. In addition, the traffic throughput always exceeds
26.9%, regardless of the number of packet types or the
distribution of traffic between them. The performance
of the Reservation Header Variable Length Slotted Aloha
protocol has been evaluated for packets 2^k long, but the
analysis is general enough to accomodate any choice of
packet lengths which satisfy the mutually divisible lengths
condition. If the allowed packet lengths are selected to
match the message lengths, the message throughput of RHVLSA

will exceed that of Slotted Aloha, due to the reduced
overhead when a message is transmitted in a single packet,
and to the gain obtained by scheduling long packet trans-
missions using reservations.

The RHVLSA protocol should be considered as an
effective alternative in applications which currently
employ Pure or Slotted Aloha for variable length messages,
including mixed-mode protocols which integrate pure
reservation and Aloha techniques.

REFERENCES

1. Tobagi, F.A., "Multiaccess Protocols in Packet
    Communication Systems", IEEE Trans. Commun.,
    p. 468, April 1980

2. Roberts, L.G., "Dynamic Allocation of Satellite
    Capacity Through Packet Reservation",
    National Computer Conference, Vol. 42, 1973

3. Wieselthier, J.E., and Ephremides, A., "A New
    Class of Protocols for Multiple Access in
    Satellite Networks", IEEE Trans. Automatic
    Control, Vol. 25, p. 865, October 1980

4. Abramson, N., "The ALOHA System-Another Alternative
    for Computer Communications", Proc. of AFIPS
    Fall Joint Comp. Conf., Vol. 37, pp. 281-285, Nov. 70

5. Roberts, L.G., "Aloha Packet System with and without
    Slots and Capture", Comp. Commun. Revue, April 1975

6. Capetanakis, J.I., "Tree Algorithms for Packet
    Broadcast Channels", IEEE Trans. Info. Theory,
    Vol. IT-25, Sept. 1975,pp.505-515

7. Humblet, P.A., and Mosely, J., "Efficient Accessing
    of a Multiaccess Channel", IEEE Conf. on
    Decision and Control Dec.1980

8. Gallager, R.G., "Conflict Resolution in Random Access
    Broadcast Networks", Proc. FOSR Workshop in
    Commun. Thy. & Appl., Sept. 1978

9. Lam, S.S., and Kleinrock, L., "Packet Switching in a
    Multiaccess Broadcast Channel: Dynamic Control
    Procedures", IEEE Trans. Commun., COM-23 Sept. 1975

10. Ferguson, M.J., "A Study of Unslotted Aloha with
    Arbitrary Message Lengths", Data Commun. Symp. 1975